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The HDBTDC AOA was performed in three steps. Under Step 1, measures of performance and measures of effectiveness were defined. In addition, representative hard targets were chosen for the template target set and defeat mechanisms were defined for each template target. In Step 2, a screening analysis was completed using simplified algorithms to analyze the effectiveness of the conceptual weapon systems against the template target set. The weapon system concepts were compared within categories to select the most promising candidates for additional analysis. Based on this comparison, generic weapons were designed to improve performance in each category. In Step 3 a detailed analysis was completed in which the best systems in each category from Step 2 and the generic weapon concepts were evaluated in more detail using the Modular Effectiveness and Vulnerability Assessment (MEVA) code.

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Hard and Deeply Buried Target Defeat Capability Analysis of Alternatives Lethality Approach

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ABSTRACT

The Hard and Deeply Buried Target Defeat Capability (HDBTDC) Analysis of Alternatives (AOA) was a tri-service effort led by the Air Force Air Combat Command (ACC) and Air Force Space Command (AFSPC) to determine the best weapon system solution for the defeat of hard and deeply buried targets. This paper describes the methodology and approach used for the lethality analysis portion of the HDBTDC AOA.

The HDBTDC AOA was performed in three steps. Under Step 1, measures of performance and measures of effectiveness were defined. In addition, representative hard targets were chosen for the template target set and defeat mechanisms were defined for each template target based on the target function and the amount of intelligence data available on the specific target. In Step 2, a screening analysis was completed that used simplified algorithms to analyze the effectiveness of the conceptual weapon systems against the template target set. The weapon system concepts were then compared within categories to select the most promising candidates for additional analysis. Based on this comparison, generic weapons were designed to improve performance in each category. In Step 3 a detailed analysis was completed in which the best systems in each category from Step 2 and the generic weapon concepts were evaluated in more detail using the Modular Effectiveness and Vulnerability Assessment (MEVA) code. Step 3 also included an excursion analysis that tested the robustness of weapon system concepts against targets for which there is uncertainty in physical and functional definition.

INTRODUCTION

There has been a trend in recent years to place high value military assets in hardened structures. This includes command and control operations as well as weapons of mass destruction. As a result, there is a need to develop conventional weapon systems with the ability to defeat these hardened targets. The purpose of the Hard and Deeply Buried Target Defeat Capability (HDBTDC) Analysis of Alternatives (AOA) was to analyze the effectiveness of a set of weapon concepts in defeating or destroying hard and deeply buried targets. The HDBTDC AOA was a three-year multi-service effort led by Air Combat Command (ACC) and Air Force Space Command (AFSPC). A contractor team led by TRW and including Applied Research Associates and Veridian, supported the analysis to find a system to hold hard and deeply buried targets at risk.

The HDBTDC AOA was completed in three steps. Step 1 was the process and data definition stage where data on the concept weapon systems were gathered, the target set was chosen, and the Measures of Effectiveness (MOE) and Measures of Performance (MOP) were defined. Step 2 was an initial assessment of the concepts using simplified analysis techniques. The best systems from the Step 2 analysis were then evaluated more rigorously in Step 3 to determine the best system from a cost and effectiveness standpoint. This paper will focus on the portion of the analysis directly concerned with the weapon target interaction. Results of this study and approach for the mission, campaign, and cost analyses can be found in the HDBTDC Final Report (2000).

STEP 1

Under Step 1, the study analysis process was defined. This included choosing the Major Theater War (MTW) scenarios for the mission and campaign analyses, choosing representative targets for the lethality analysis, and defining effectiveness measures. The functional objectives (FOs) and MOEs that were defined are shown below in Table 1. The results of the lethality analysis fed directly into the number of weapons to defeat the MTW target set (MOE 1.3a) and the percentage of worldwide targets held at risk (MOE 3.1).

The most important part of Step 1 for the lethality analysis was the target set selection and definition of defeat mechanisms. For the HDBTDC AOA, Twenty-six hard targets, referred to as the Target Template Set (TTS), were chosen to represent the range of target functions and hardness found in worldwide hard targets. These twenty-six targets were used as surrogates for the wide range of real hard targets found in the scenarios. For each target in the scenario, a TTS target was determined to be its best match functionally and structurally in the process of mapping the TTS targets into the scenario.

Defeat mechanisms were defined for each member of the TTS based on the function of the target as well as the amount of intelligence data available on the target. Three defeat mechanisms were used in the main portions of this study: perfect knowledge functional defeat, adit functional defeat, and structural defeat. Perfect knowledge functional defeat assumed detailed knowledge of the target including the location of critical nodes for the facility. For this defeat mechanism, the defeat of each relevant critical node, for example,

power, HVAC, or communications, was analyzed.

assumed to use the hard target smart fuze or advanced hard target smart fuze.

Table 1. Functional Objectives and Measures of Effectiveness for the HDBTDC AOA

FO	MOE
1. Defeat MTW hard and Deeply Buried Targets Within Scenario Timelines	1.1 Percentage of MTW Targets Defeated 1.2 Mission Response Time (Mission Completion Time) 1.3a Number of Weapons Required to Defeat MTW Target Set 1.3b Number of Sorties Required to Defeat MTW Target Set.
2. Minimize Resusable Platforms Lost During Defeat of MTW Target Set	2.1 Number of Delivery and Support Platforms Lost
3. Hold Worldwide Hard and Deeply Buried Targets at Risk	3.1 Percentage of Worldwide Targets Held at 3.2 Mission Response Time 3.3 Number of Delivery and Support Platforms Lost
4. Minimize Collateral Damage	4.1 Number of Facilities Damaged Other — Planned 4.2 Number of Civilian Casualties

Adit functional defeat was assessed for deep underground and tunnel targets where detailed functional knowledge of the interior of the target was unknown or the functional interior of the target could not be reached with conventional weapons. To achieve adit functional defeat, a weapon was required to fill 10 meters of tunnel length with rubble by detonating in the rock above the tunnel. For all of the twenty-six targets structural kill was assessed, which required collapse of the roof over 50% of the facility area. For a subset of the targets, where no information on the equipment layout inside was available or where the target's primary function was storage, structural kill was the only defeat mechanism assessed.

Additionally in Step 1, assumptions and rules for the lethality analysis were defined. The primary assumption for the lethality analysis was that the concepts and legacy weapons were evaluated for optimal impact conditions. This was done so that the comparison of results would be for the best performance of each weapon. Also, all weapons were

Several assumptions were made for the penetration analysis. There is little data about the survivability of the warhead case during high velocity impacts so the failure rate was extrapolated from low velocity weapons. Additionally, there was little data for weapon case failure during rock penetration, so the failure rate was extrapolated from failure rates into concrete.

The final assumption for the lethality analysis was that no more than 50 weapons would be used against a single target. This cutoff was used to limit the lethality calculations and was deemed to be a large enough number such that all concepts would be given enough opportunity to show their effectiveness. In the mission analysis, CONOPS restrictions limited this number further for particular weapons and weapon groups.

STEP 2

In the Step 2 lethality analysis, fifty-five concept weapons and nine legacy weapons were evaluated against the

twenty-six template targets. In this step a simplified analysis was done to screen the weapon concepts and determine which were the most promising candidates for evaluation in the Step 3 analysis. The final results of the lethality analysis were tables containing the number of concept applications necessary to produce an 80% probability of kill for each defeat mechanism for every target. All the lethality calculations were run for six different CEPs: 1, 3, 5, 9, 12, and 30 meters. In the Step 2 mission analysis actual weapon CEPs were determined based on the weather and jamming environments and corresponding lethality results were interpolated from the data in the tables.

The first step in evaluating weapon effectiveness against hardened targets is to calculate the weapon penetration into the target. In this study, cross-sectional layered versions of the targets were used with the Simplified Analytical Model of Penetration with Lateral Loading (SAMPLL) code to calculate the penetration of the rigid body penetrators. SAMPLL is a semi-empirical tool that uses empirical equations to calculate penetration and basic engineering principles to calculate kinematics and stress during each time step (Young 1992). The empirical penetration equation is:

$$D = 0.00178 \times S \times N \left(\frac{W}{A} \right)^{0.7} (V - 100) \quad (1)$$

where S is the penetrability number, N is the nose coefficient, W/A is the areal density in lbs/in2, and V is the impact velocity in feet per second. The nose coefficient is calculated for ogive shaped noses as

$$N = 0.18 \frac{L_n}{d} + 0.56 \quad (2)$$

The S-number for penetrability depends on the material and usually ranges from 4 to 8 for soil and 0.8 to 1 for concrete.

For the layered targets used in the study, the topsoil was given an S-number of 8, soil in between concrete layers was given an S-number of 4, and concrete was given an S-number of 1.

To evaluate penetrator motion, SAMPLL calculates the axial load exerted on the penetrator nose and the lateral loads due to the angle of attack and trajectory angle. These loads are used to calculate the penetrator translational and rotational accelerations, which are then integrated to determine the path of the penetrator through the target.

Once it was determined the weapon could penetrate the target, the blast effects were calculated. For the air blast effects, a case reduced explosive weight was used. For a cased weapon, some percentage of the energy of the detonation is used to expand and break apart the case. This energy is then unavailable for blast damage. The modified Fano equation is shown in Equation 3, where w is the actual explosive weight and M/C is the metal-to-charge ratio of the warhead, was used to calculate the case reduced explosive weight.

$$w_{equiv} = w \cdot \left[0.6 + \frac{0.4}{1 + 2 \cdot (M/C)} \right] \quad (3)$$

The metal-to-charge ratio can be calculated with the following equation:

$$M / C = \frac{(R1^2 - R2^2) \cdot \rho_{case}}{R2^2 \cdot \rho_{explosive}} \quad (4)$$

where $R1$ is the external case diameter, $R2$ is the internal case radius, ρ_{case} is the density of the case, and $\rho_{explosive}$ is the density of the explosive. To determine the TNT equivalent explosive weight the conversion factor from the explosive type to TNT is multiplied by the case reduced explosive weight.

Once the uncased equivalent TNT explosive weight for the concept is known, the effectiveness of the weapon can be calculated. For perfect knowledge functional defeat, the target is known in enough detail to determine a single aimpoint where a particular critical node is located. Given the size of the room in which the critical node is located and the effective explosive weight of the warhead, the range within which the weapon is effective against the equipment of interest can be determined from the curve shown in Figure 1.

where r_{breach} is the breach range in feet, w_e is the uncased equivalent TNT weight of the warhead in pounds, and t_{wall} is wall thickness in feet. Based on these breach and overpressure curves, an effective room area was determined. If a single weapon is able to penetrate to the aimpoint and has enough explosive weight to kill the critical node in the room the probability of effectiveness is just the probability of hitting within the effective room area. The probability of hit is calculated as a function of the weapon CEP and the size of the effective
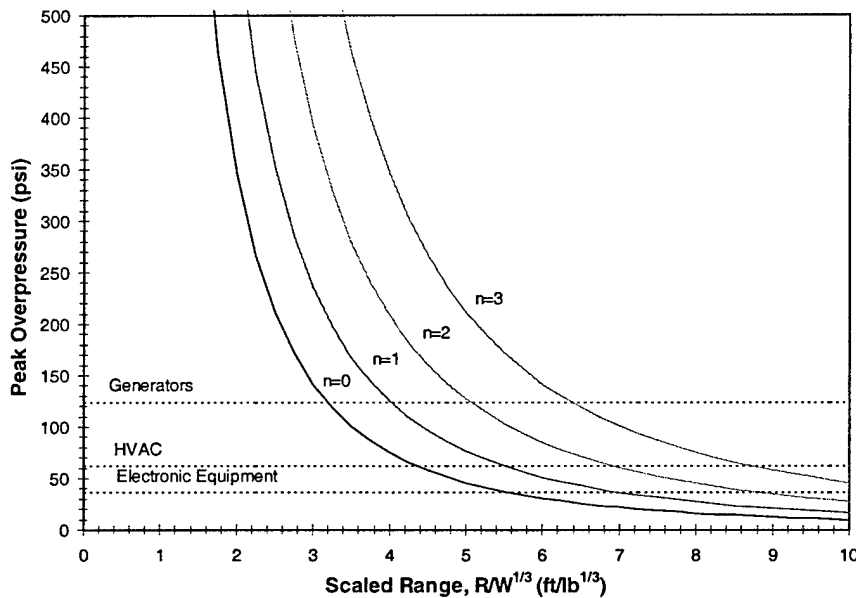

Figure 1. Peak Overpressure versus Scaled Range.

Some weapons with large explosive weights are able to breach a wall in the target and kill critical equipment in an adjacent room. To determine whether the weapon has enough explosive weight to breach the wall of the room and still defeat the critical node, the following equation is used

$$r_{breach} = \frac{0.46 * (4 * w_e)^{1/3}}{0.05 + \frac{t_{wall}}{0.18 * (4 * w_e)^{1/3}}} \quad (5)$$

room area using the normal distribution. Given this probability of hit (Phit), the number of weapons required to defeat the target can be simply calculated as

$$N = \frac{ln(1 - 0.8)}{ln(1 - Phit)} \quad (6)$$

When the weapon has enough explosive to kill the room with critical components but does not penetrate, the crater size produced by the weapon above the target is calculated. The height

of the crater is calculated using equation 7.

$$H = 4w^{1/3}\left(1 + \sqrt{1 + \frac{f'_c}{17.0\sqrt{f'_c}}}\right) \quad (7)$$

where w is the explosive weight and f'_c is the strength of the concrete. The crater is modeled as a 40 degree truncated cone and the average radius was used in the subsequent probability calculations. Based on the crater height, the number of weapons needed to hit the same hole in order for a single weapon to reach the room was determined. If more than 3 weapons were needed to dig into the target, the weapon was considered to be ineffective against the target. The probability of a penetrator forming a crater, P_c, is just the probability of hitting the area of effectiveness, P_H. The probability of a subsequent penetrator hitting the crater given a hit is

$$P_{HC|H} = \frac{\text{Crater Area}}{\text{Target Area}} \quad (8)$$

This approach sometimes penalizes larger targets since it assumes that the initial crater is just as likely to form near the aimpoint as the edge of the target. For this reason if the optimum target area was smaller than the actual target area then the optimum target area was used. If n weapons are needed for penetration the probability that at least (n-1) penetrators will hit the crater assuming the crater has already been formed by the jth weapon dropped is

$$\sum_{i=n-1}^{N-j}\binom{N-j}{i}P_{HC}{}^i\left(1 - P_{HC}\right)^{N-j-i} \quad (9)$$

The probability that the jth weapon will be the first penetrator to form the crater is

$$(1 - P_C)^{j-1}(P_C) \quad (10)$$

Therefore the total mission effectiveness is

$$ME = \sum_{j=1}^{N-n+1}(1 - P_c)^{j-1}(P_c)\left[\sum_{i=n-1}^{N-j}\binom{N-j}{i}P_{HC}{}^i\left(1 - P_{HC}\right)^{N-j-i}\right] \quad (11)$$

The total number of concept applications, N, needed is found by iterating on N until the mission effectiveness is greater than or equal to 0.8.

For the adit functional defeat, the geologic layers above the tunnel were characterized and the amount of rubble required to fill 10 meters of tunnel length was calculated based on the width and height of the tunnel. A code called TunnelSpall was used to calculate the rubble volume produced by a single as a function of distance from the roof of the tunnel to the detonation point, known as the standoff. TunnelSpall uses the DUG-1C methodology for shock propagation and the properties of the rock layers above the tunnel, such as unconfined strength, density, and seismic wave speed, to determine how much rubble is deposited into the tunnel. Inputs to the code include the tunnel dimensions and properties of the geologic layers above the tunnel. A sample rubble volume versus standoff curve is shown in Figure 2. As shown in the figure, there is an optimum standoff that produces the most rubble. This optimum standoff is a function of explosive weight, such that for larger explosive weights the optimum standoff is farther from the tunnel roof. Given the weapon penetration calculated with SAMPLL, the number of weapons needed to fill the tunnel with rubble for 10 meters is determined from the curve. If the weapon can reach the optimum standoff, the optimum rubble volume was assumed. If the weapon could not reach the optimum standoff, the rubble volume for the best standoff the weapon could achieve was used. For the

simplified Step 2 analysis no fuzing was explicitly modeled, it was assumed that if a weapon could reach the point of optimum standoff that it would detonate at the point of optimum standoff.

required to overcome the shear capacity and dead load of the roof was determined using equation 12, where P_{qs} is the quasi-static pressure in psi, L is the span of the room in inches, f'_c is the
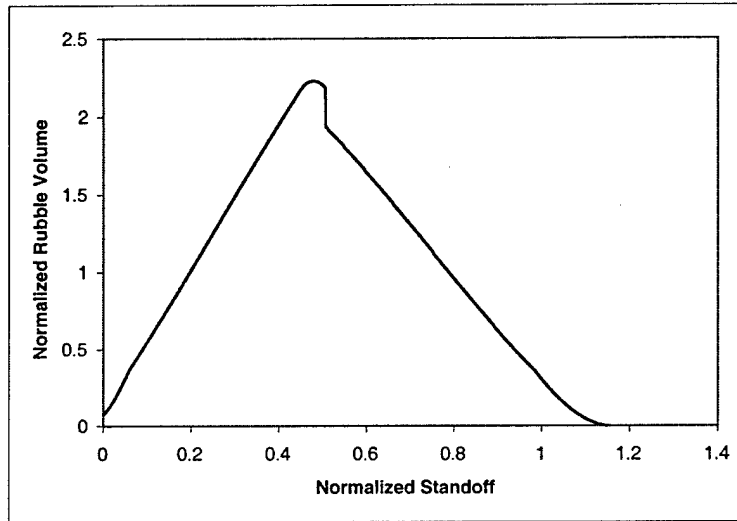

Figure 2. Rubble Volume Versus Standoff Curve

For Adit Functional Defeat, the aimpoint area was assumed to be the tunnel width by 10 meters. The probability of hit for a single weapon was calculated as a function of the aimpoint area and the CEP using the normal distribution. The number of weapons needed to produce enough rubble to defeat the adit was calculated as the total rubble volume required divided by maximum rubble volume produced by a single weapon. The probability of kill was calculated using the binomial distribution as a function of the probability of hit, the number of weapons needed to produce the required rubble, and the number of weapons delivered.

For the Step 2 structural defeat calculations, the target was divided into small, medium, and large rooms and the percentage of total target area made up of each room size was calculated. For each room size, the quasi-static pressure

concrete strength in psi, t_{roof} is the roof thickness in feet, t_{conc} is the total concrete overburden thickness in feet, and t_{soil} is the total soil overburden thickness if feet.

$$\tfrac{1}{2}P_{qs}L = 7\sqrt{f'_c}(t_{roof}) + 12(t_{conc}) + 8(t_{soil}) \quad (12)$$

Given the quasi-static pressure, the critical explosive weight necessary to drop the roof for each room size is calculated as

$$w_{crit} = \left(\frac{P_{qs}}{9897.3}\right)^{\tfrac{1}{0.933}} * V \quad (13)$$

where w_{crit} is the critical explosive weight in lbs and V is the room volume in ft3. This pressure/volume relationship provides a means of estimating the room size that each concept can kill. If the effective explosive weight is large enough, the concept may breach the walls of the room and kill additional rooms. Based on the weapon explosive weight and the distribution of rooms and sizes, the number of hits required to

defeat the target was calculated. Given on the number of hits, a grid was determined for the target. The probability of hitting this grid or aimpoint area was calculated as a function of the aimpoint area and CEP using the normal distribution. The number of hits required and the probability of hit were used in the binomial distribution to determine the number of weapons necessary for the 0.8 probability of kill for the target. In the case of structural defeat, only weapons that could fully penetrate the target were able to achieve the defeat.

GENERIC WEAPONS

Near the end of Step 2, the weapon concepts were divided into three categories for comparison: direct attack munitions, cruise missiles, and conventional ballistic missiles. The Step 2 lethality and mission results were used to rank the concept weapons in each of these three categories. From these results, it was obvious that each category had particular strengths and weaknesses. It was also apparent that certain optimizations could be performed on weapons from each set to improve the performance against the TTS. For this reason, generic weapons were designed to optimize performance and to make sure that the trade space of weapon configurations was covered.

The graph in figure 3 is a qualitative representation of a plot of explosive weight and penetration capability, the two primary factors in determining the effectiveness of a weapon against hard targets. On average, direct attack munitions have relatively high explosive weights, but moderate to low penetration capabilities. For these weapons, one can generally trade explosive weight for penetration capability, for example, by making the diameter of the weapon smaller. On average, cruise missiles have moderate explosive weight and low penetration capabilities. For these systems it is more important to try and improve the penetration capability without losing much explosive, for example by redesigning the nose. On average, conventional ballistic missiles have high penetration capabilities because of their high impact velocities, but low explosive weights, so we can trade penetration capability for explosive weight, for example by increasing the weapon diameter. Using these guidelines, a set of optimized generic weapons was developed for evaluation in the detailed Step 3 analysis along with the best concepts evaluated in Step 2.
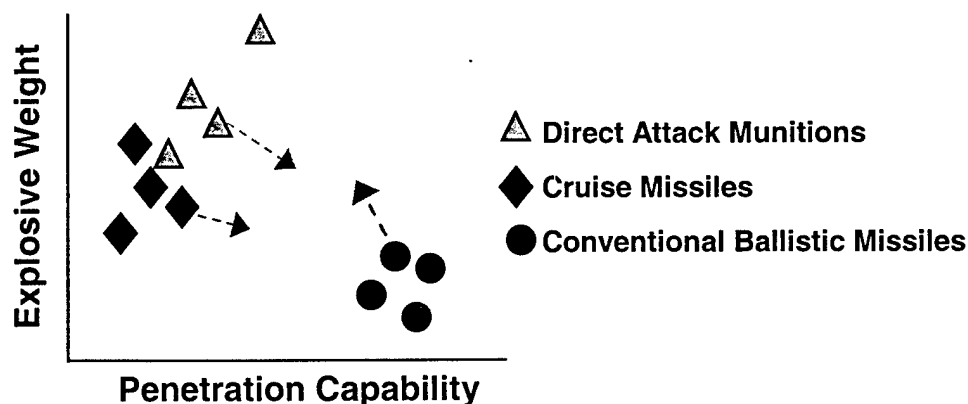

Figure 3. A Qualitative View of Explosive Weight Versus Penetration Capability

STEP 3

For the Step 3 lethality analysis, the effectiveness of ten concept weapons and sixteen legacy weapons against the TTS was evaluated. This evaluation was performed using the Modular Effectiveness and Vulnerability Assessment (MEVA) code. MEVA performs a Monte Carlo analysis, modeling penetration, fuzing, and damage propogation for conventional weapons against ground-fixed targets (Dunn et al. 1998). MEVA is composed of modules, which are independently compiled and linked C++ programs, that perform the various pieces of the analysis. For the HDBTDC AOA, the SAMPLL Regression Penetration and Grid Airblast modules were used. One hundred iterations were performed for each concept weapon assuming a bivariate normal delivery pattern.

Inputs to MEVA include a target physical definition in BRL-CAD or target description language (TDL) format and, if available, a target functional definition in the form of a fault tree. The physical description of the weapon is also input along with mean impact conditions and associated uncertainties. Fuze settings for the weapon, including the number of voids to detect and the delay for the hard target smart fuze, are also required.

Lethality results for perfect knowledge functional defeat and structural defeat in Step 3 were calculated with the same methodology as in Step 2, but using MEVA to explicitly model fuzing and cumulative effects from multiple weapons. The Step 3 approach to modeling adit functional defeat augmented the Step 2 analysis with modeling of actual burst points using MEVA penetration modules. The MEVA calculations produced a set of weapon burst points for a given target and CEP. A simple code was produced to read in these burst points and calculate the effective standoff, or distance from the burst point to the tunnel roof. Given a standoff and explosive weight, the amount of rubble produced at a particular burst point was calculated from the rubble volume versus standoff curve shown in Figure 3. For each burst point the amount of additional rubble produced was added to the rubble from the previous burst points until enough rubble was obtained to defeat the target.

The results of the Step 3 calculations were delivered in the form of number of weapons for a 0.8 probability of kill for each weapon and target combination for each of the six CEPs.

EXCURSIONS

After completing the baseline Step 3 lethality results, excursion calculations were performed to evaluate the effect certain assumptions on the results. The first excursion analyzed an alternate defeat mechanism to replace structural defeat. This was motivated by the fact that a large number of weapons are required for structural defeat and for many warheads with low explosive weights structural defeat may not be achievable within the fifty weapon limit. This was of particular importance because when the surrogate TTS targets were mapped into the targets in a scenario, they were mapped based on intelligence information available on the actual target. For example, if the template target of interest was detailed enough to be evaluated for functional kill, it was unlikely that the real world target it was mapped to would be known in such detail. Therefore it was mapped in as a structural kill. In this manner, the

requirements for structural kill were very strong at the mission level and there were concerns that this was unfairly penalizing certain concepts.

Therefore, two alternate defeat mechanisms were created. The alternate defeat mechanism for non-storage targets required the defeat of a critical node of the target using geometric aiming. This criterion is similar to Perfect Knowledge Functional Defeat except that detailed knowledge of the interior of the target is not required. The second alternate defeat mechanism was evaluated for WMD storage targets and requires that enough of the target is covered to destroy 50% of the storage containers in the target using geometric aiming. Selected results were calculated using MEVA and based on the MEVA results an algorithm was developed to quickly estimate the number of weapons needed to functionally defeat a target using geometric aiming. These results were then folded into the mission level results by changing the target mapping such that whenever structural kill was required, now the alternate defeat was required.

and what particular target parameters have the most impact on weapon performance. Two types of calculations were done for these excursions. The first took four of the 26 template targets and, using the standard target description as the mean, randomly generated 100 instantiations of each target. In each of these instantiations, the thickness of the structural components, the strengths of the structural components, and the locations of the functional components were varied based on a rule set determined by the HDBTDC AOA working groups and the Defense Intelligence Agency (DIA). The rule base is shown in Table 2.

A script was set up to have MEVA run with a new target instantiation for each of 100 iterations. This first set of calculations provided an indication of the effect of randomizing all the uncertainties. To single out which uncertainties are the most crucial, a parametric study was done where only one parameter in the target was changed for each analysis. For example, the total thickness of the roof was changed for one run while all other parameters

Table 2. Target Uncertainty Bounds

Component	Uncertainty Bounds and Rules
Concrete Thickness	±50% for Concrete Components ≤ 1 meter thick ±20% for Concrete Components > 1 meter thick
Concrete Strength	3000 – 6000 psi
Soil Strength	S-Number of 4 – 11
Critical Components	Equipment in a Given Room Stays Together Power and HVAC Equipment Located on Bottom Floor Power and HVAC Equipment Located Along Outside Walls

The second excursion involved target uncertainty. In the real world it is unlikely that target physical descriptions will be known perfectly. These excursions aimed to determine how this uncertainty effects weapon performance

remained the same.

QUERY TOOL FOR AOA RESULTS (QTAR)

As the HDBTDC AOA final report was being produced, it became obvious that there was an overwhelming amount

of data produced in the study. In addition, there were still many questions being asked, such as how would the results change if the explosive weight of one weapon concept were changed slightly. The Query Tool for AOA results was developed to provide access to the large amount of data from the study as well as to answer some of these questions. QTAR is a calculational database that allows one to sort and query the official data and additionally to perform simple calculations on new inputs, for example to calculate the penetration capability into infinite concrete of a new weapon configuration. In addition to numerical tables, it contains supporting graphical data for the targets, weapon systems, and platforms used in the study. It also contains a GIS capability to plot the locations of the scenario targets. A view of the QTAR graphical user interface (GUI) is shown in Figure 4.

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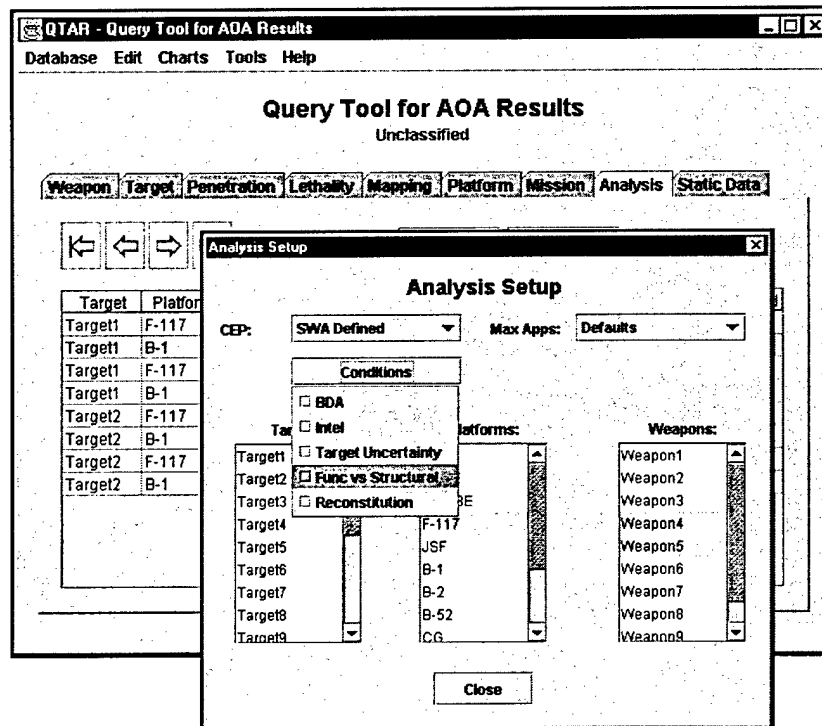
Figure 4. QTAR GUI